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Review of utilization of extended surfaces in heat transfer problems

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ABSTRACT

This review presents when and how extended surface with heat exchanger have been used over the last 15 years in the field of heat transfer. They have been used in this field over a century, but their utilization increases more recent. For past 1 decade, most of the industries required high performance heat transfer components with less weight, volume and cost. The reported investigations are categorized into five major groups as follows: annular fins, elliptical fins and elliptical tube, pin fins, longitudinal fins and recent trend fins by experimental, numerical and analytical methods. Around 70 published articles related to fins with heat exchanger are briefly reviewed. This information is useful for future use of the different shapes of extended surface based on the space availability and cost.

Contents

1. Introduction

The operation of several engineering systems results in the generation of heat. This may cause severe overheating problems and occasionally leads to failure of the system. This system needs superior heat transfer elements with increasingly smaller weights, volumes and cost. The heat generated in a system such as transformers, refrigerators, boiler super-heater tubes, condenser coils, electronic components, compressors, air cooled engines, etc. must be dissipated to its surroundings in order to maintain the system functioning at its recommended working temperatures and operating effectively and reliably. From the literature review [4], they reported many methods that were proposed to achieve this goal. Bergles classified these methods as active and passive

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methods. Active methods are those requiring external power to maintain their enhancement such as well stirring the fluid or vibrating the solid surface. On the other hand, the passive methods do not require external power to maintain the enhancement effect as when fins are utilized.

Heat transfer by convection between a surface and the fluid surroundings can be augmented by attaching thin strips of metal called fins. Fins are adjunct attached to the primary heat transfer surface to increase the heat transfer rate at the air side primarily by increasing the air side heat transfer area. Since the use of extended surfaces has been often more economical, convenient and trouble free, most proposed applications of increasing surface area is adding fins to the surface in order to achieve the required rate of heat transfer. However, the designer should optimize the spacing or the number of fins on base carefully; otherwise fin additions may cause the deterioration of the rate of heat transfer. Although adding numerous fins increase the surface area, they may resist the air flow and cause boundary layer interferences which affect the heat transfer adversely [1–4]. The amount of heat flow through a fin requires knowledge of temperature distribution through the fin. The temperature distribution in a fin will depend upon the properties of both the fin material and the surrounding fluid. To determine the most cost-effective material for any application is no simple task when costs and performance are properly assessed.

Recently, requirement of enhanced heat transfer has been very much essential in electronic and industrial components designing because the power of the computer, micro-processors doubles every 18 months, keeping their volume constant. The necessity of ever higher specific powers leads to increasing the number of the modular computing units inserted into the surface allocated to the CPU. Also the intense increase of performances determines a consequent enhancement in the thermal power generated by the components. This leads to the need of an ever more effective cooling, to avoid malfunctions.

The addition of fins causes to extend the initial price, weight, and pumping power needed under forced convection conditions. For this reason, there are numerous researches within the literature already concerned within the optimum fin style. Naturally optimization of the fin shapes is of nice interest for several engineering topics. The optimization to find the shapes and dimensions of the fins that has ordered out two perspectives—First cluster of optimization issues involves the determination of the profile of the fin so for a given quantity of heat transfer rate, the degree of the fabric used could be a minimum. Another cluster is to work out the fin dimensions for a given fin form and a desired cooling rate so that the degree of fabric used would be a minimum. Utilization in the primary approach of optimization, several researchers have targeted their studies to get the profile form of a fin. These profiles are also parabolic, circular, or wavy in nature. However, these profiles might not be utilized since these are expensive in production and fabrication. On the opposite hand, the second approach of optimization is, thus, a lot of engaging in the fin optimization issues.

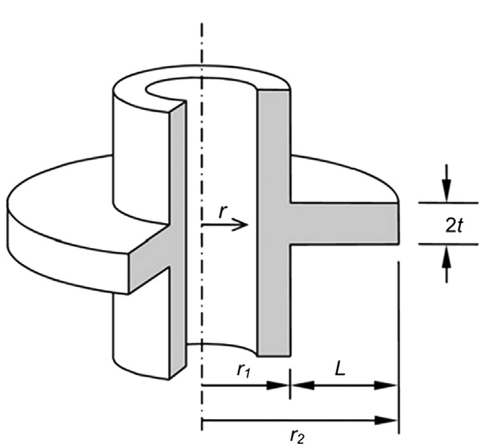

Fig. 1. Schematic of an annular fin of uniform thickness.

To overcome the above difficulties different kinds of shapes and sizes of fins can be employed to the surface depending upon the application and nature of the designs. Normally plate fins, annular fins and pin fins are used for heat transfer. Following the previous cited reviews, the main objectives of this review work can be formulated as follows: (I) a summary of the studies reported with various types of fins, and (II) the identification of the future research needs of availability space and cost.

2. Studies on annular fins with circular heat exchangers

2.1. Introduction

Annular fins notice varies applications in compact heat exchangers, in specialized installations of single and double-pipe heat exchangers, in electrical equipment within which generated heat should be expeditiously dissipated, on cylinders of air cooled internal-combustion engines, etc. Fig. 1 represents the schematic of an annular fin of uniform thickness from [5]. Thermal designers face a challenge of accommodating increasing power density within a given volume and envelope form. This demands non-conventional and innovative style of heat sinks.

2.2. Studies on numerical technique

Esmail et al. [5] has presented a paper on annular fins with different profiles and reported the deviation between the fin efficiency calculated based on constant heat transfer coefficient and variable heat transfer coefficient with different radius ratios and dimensionless parameters. The authors [6] reported the temperature variation in annular fins of uniform thickness, by the mean value theorem for simplifying the modified Bessel differential equation. And they reported that the fin efficiency by the integral-based η furnishes more accurate results than the alternate derivative-based η. Differences between the analytic temperature approximation developed in the present work and the exact analytic temperature distribution relying on the Bessel functions were probably below the level of inaccuracy introduced by the Murray–Gardner assumptions on both exact and approximate temperatures. The computational methodology described in this work may find application in a broad class of the fins of variable cross section, such as longitudinal and annular fins of triangular, parabolic or hyperbolic profile.

Arslanturk [7] has reported the one-dimensional thermal analysis and optimization of annular fins with uniform thickness. He obtained the optimum dimensions of the annular fins analytically. From the derived condition of optimality, two correlation equations which express the maximum heat transfer rate and optimum radii ratio of the fin as functions of the fin volume and the Biot number are presented in Eq. (1). The simple equations serve to a designer for optimum design of annular fins with uniform thickness.

$$q{*}\lambda{*} = (a + bv + cv^2)[d + e\ \ln(\mathrm{Bi}) + f\ \ln\,(\mathrm{Bi})^2] \quad (1)$$

Yu et al. [8] discussed the optimization of rectangular profile circular fins with variable thermal conductivity and convective heat transfer coefficients. They solved non-linear conducting, convecting and radiating heat transfer equation by the differential transformation method. It was shown that the thermal conductivity

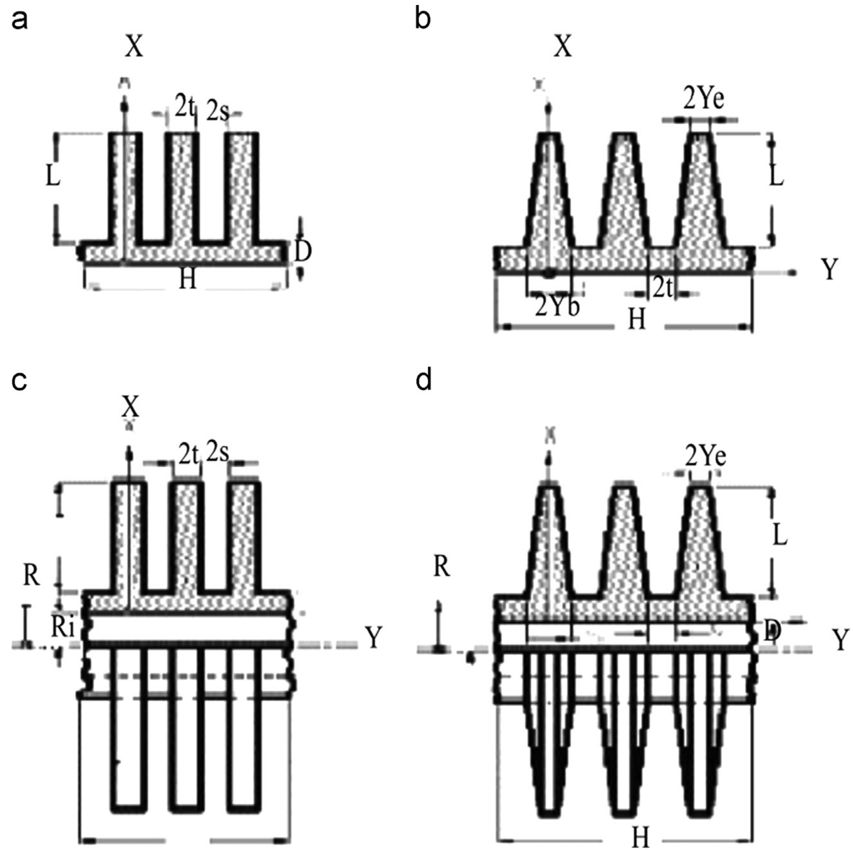

Fig. 2. Different types of fin arrays: (a) LRFA, (b) LTFA, (c) ARFA and (d) ATFA.

and heat transfer coefficient were constant for a given fin volume, the optimum fin length was almost independent of the fin-base temperature for pure convection. For both convection-radiation and pure radiation, the length of the optimum fins for higher temperatures was shorter than the length of the fins with lower temperatures.

The author et al. [9] have developed a model to analytically carry out the performance and optimum design analysis of four fin arrays, namely, longitudinal rectangular fin array (LRFA), annular rectangular fin array (ARFA), longitudinal trapezoidal fin array (LTRA) and annular trapezoidal fin array (ATFA) under convective cooling conditions as shown in Fig. 2. The analysis was established for different conductivities for the fin and the primary surface and different heat transfer coefficients for the fin surface and the inter-fin spacing. The performance parameters such as fin efficiency, fin effectiveness and augmentation factor were evaluated for a wide range of design variables. It has been observed that the conduction through the supporting structure and the convection from the inter-fin spacing have a prominent effect on the performance of a fin array. The optimum fin dimensions in a fin assembly have been determined by the consideration of the constant total height of the fin assembly and inter-fin spacing. From the results, it can be highlighted that the optimum fin dimensions in fin arrays differ from that of the individual fins.

The effects of fin spacing on four-row annular-finned tube bundles in staggered and in-line arrangements were investigated by the three-dimensional numerical study as reported by [10]. They used the renormalization group theory (RNG) based k–e turbulence model to calculate the unsteady flow and conjugate heat transfer. Based on the flow visualization results, the boundary layer developments and horseshoe vortices between the fins were found to be significantly dependent on the fin spacing to height ratio and Reynolds number. The horseshoe vortex effect was clear in the largest fin spacing and at a higher velocity. For the particular range of study, the heat transfer coefficient of the staggered arrangements is found to increase with s/h_f up to s/h_f 0:32 and then, it remains almost constant. For in-line arrangement, the heat transfer coefficient increases in the whole investigated parameter range. The pressure drop decreases for both tube arrays when s/h_f is increased. Heat transfer results consent well with existing experimental correlations. For the pressure drop, numerical results deviated more from available correlations, especially for in-line cases.

The authors [11] analyzed the straight fin of lineal profile and the annular fin of hyperbolic profile, along with a reasonable range of geometric dimensions and heat transfer coefficients. The results of the numerical, 2D calculations were compared with the 1D approximation and the errors were analyzed. The excessive values of conductivity ratios combined with a tapered longitudinal profile assured that any 1D approximation will incur the highest possible errors. This study can be considered as a general assessment of the engineering treatment of composite fins of slender profile.

The above literature review reported about thermal analysis and optimization of the annular fin with different profiles by the numerical technique. It shows that the numerical technique is economic and time saving.

2.3. Studies in experimental technique

In the paper [12] the authors explained the performance of a coated finned tube in the generator for absorption chillers by experimental methods. The radial temperature profile along the fin was modeled by lumping the energy contents of aluminum and the bonded zeolite into an effective heat capacity. Based on the computed heat transfer to the fin, the inferred coefficient of

performance was 42%; this could be improved by eliminating the interfacial resistance and optimizing the fin thickness.

The finite difference method in conjunction with the least-squares scheme and experimental temperature data was proposed by Chen et al. [13–16] to predict the average heat transfer coefficient and fin efficiency on a vertical square fin and circular fin of one-circular tube plate finned-tube heat exchangers for various air speeds and fin spacing under the free and forced convection. They reported that the value of heat transfer coefficient increases and efficiency decreases with increase in fin spacing and air speed values.

Shang-Sheng et al. [17] have investigated the transient heat transfer in two-dimensional circular fins of varied shapes with its base subjected to a heat flux variable as a sinusoidal time function. The temperature distribution of the central line increases as time increases and decreases as the distance from the base of the fin increases, and decreases as the Biot number increases, and the ratio of the outer radius to the length of the fin increases and reached the earlier steady state.

2.4. Studies on analytical technique

Lalota et al. [18] have presented a paper on the efficiency of two-material fins. The analytical solution was compared to the expression obtained by Gardner for one-material fins and concluded that Gardner's expression can be used for a two-material fin, by changing only the value of one parameter. An expression of the efficiency of fins made of two materials has been developed. A simplified expression of the main parameter was given and this approximation was justified for ordinary fin geometries. They reported that a coating with a higher thermal conductivity increases the efficiency of fins. The coating was more important for fins that have a low efficiency when they were uncoated. The efficiency ratio may be increased by a factor of two.

The present work was [19] concentrated on the performance and optimization analysis of annular step fins under wet surface conditions and the following conclusions were: (1) Dehumidification of air depends not only on the psychometric condition of air on the fin surface but also on the surface temperature of the fin. (2) Fin surface temperature for wet fins was an implicit function with the thermo-physical, psychrometric and geometric parameters. (3) For a practical range of design parameters, there was a very high chance to obtain a fully wet surface instead of a partially wet fin. (4) With the relative humidity for the fully wet fin, the error of results associated with considering the tip temperature as a dew point temperature for calculating the psychrometric parameters was an increasing function. (5) The overall efficiency of ASFs under wet conditions increases with the increase in both the geometrical parameters. (6) The optimality criteria for annular fins were established in a generalized way such that either the rate of heat transfer or the fin volume can be taken as a constant. (7) The optimum geometrical parameters determined by using the present study were also an implicit function with the psychometric parameters. However, in the previous studies, these were treated explicitly. (8) With considering dew point temperature as a tip temperature for calculating psychrometric parameters, heat transfer rate was always lower than that of the actual tip temperature under the condition of fully wet surface. However, a maximum difference was noticed at the optimum point for the 100% relative humidity. (9) Increase in ambient temperature increases the optimum heat transfer rate for the fully as well as partially wet fins. (10) Increasing both the ambient pressure and fin-base temperature decreases the rate of heat transfer for any wet fin. (11) The optimum ASF transfers more rate of heat in comparison with that of the annular disc fin for the same thermo-physical and psychrometric parameters. (12) The present analysis was equally suitable for the dry surface condition also with the consideration of zero value of the latent heat of condensation. (13) The present analysis of annular step fins was equally suitable for the analysis of annular disc fins only consideration of the geometrical parameter thickness ratio equal to one.

Leonid et al. [20] have presented a paper on a brand new minimum volume straight cooling fin taking under consideration the length of arc. The volume of the optimum circular fin found in this paper is 6.21–8 times smaller than the volume of Schmidt's parabolic optimum fin. The optimum circular fin tends to be shorter and has a larger base height than Schmidt's fin. The advantage is due to the distance from the heated wall to the fin surface which was much shorter for the former and its surface area.

Hong-Sen et al. [21] have selected the singular annular fin, divided into several circular sections, and each section heat transfer coefficient and thermal conductivity were considered. The result from each section was combined and calculated together by a recursive formula that gave the solutions of temperature distribution and heat transfer rate on singular annular fin for both conditions with and without heat transfer to fin-tip was demonstrated.

Naphon et al. [22] have reported on circular fins hear transfer characteristics and also the fin efficiency of the circular fin area unit under dry-surface conditions, partly wet-surface conditions, and absolutely wet-surface conditions. The mathematical models supported the conservation equations of energy and mass area unit developed and solved by the central finite distinction technique to find temperature distribution on the fin. There was an affordable agreement between the results obtained from this model and other researchers'.

The optimum cooling effect of a heat sink equipped with annular fins was presented in this study [23]. The optimum equation was derived in transcendental form and the formula of the thermal resistance is also provided. This optimum equation can be utilized to find the optimum outer radius of annular fins and fin number on a heat sink that affect the overall thermal effectiveness of a heat sink based on the input data of dimensionless parameters.

The above reviews reported about annular fin thermal performance and optimization analysis by numerical, analytical and experimental method under different geometric conditions, surface conditions and different spacings between fins. The following major points are identified from above reviews:

- This type of study would be of direct use for the heat transfer equipment designers and rating engineers.
- Due to the gradual decrease in heat conduction rate from the fin-base to fin-tip, effective utilization of fin material may not be possible for annular disc fins. For this reason, different

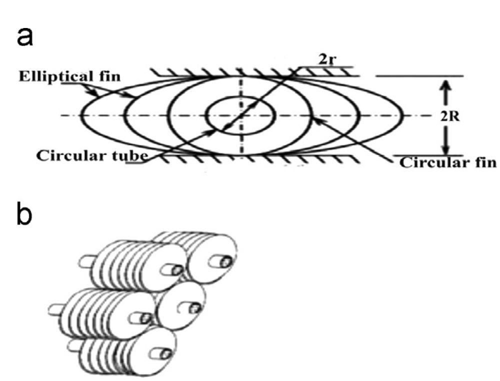

Fig. 3. (a) Elliptic fin in circular tube and (b) elliptic fin in elliptical tube.

tapered fins had already been investigated by many researchers. However, among these a very little one is compatible with the manufacturing process. Because of that annular disc fin is extensively found in various applications. Lot of investigations are still engaged to modify the geometry of the annular disc fin on the basis of enhancement of heat transfer rate as well as ease of fabrication.
- Most of papers concentrate on optimization will save time and economically.

3. Studies on annular elliptical fins and elliptical tube heat exchangers

In this paper, a brief overview of elliptical fins and elliptical cylinders and tubes are described in this section.

3.1. Studies on annular elliptical fins

Kundu et al. [24] have analyzed a paper on elliptic fins as shown in Fig. 3a by the semi-analytical technique. A technique for the optimum style of the fins, employing a constraint of either fin volume or rate of heat dissipation has been recommended. Optimum elliptical fins dissipate heat at a better rate compared with circular fin and area restriction exists on either side of the fin. Even if the restriction was on one side, the performance of elliptical fin was better than of the eccentric circular fin.

Chen-Nan et al. [25] have presented a paper on a two-dimensional fin analysis of combined heat and mass transfer in elliptic fins under the dry, partly wet and absolutely wet conditions of a for different axis ratios, Biot numbers, and air humidifies as shown in Fig. 3b. They concluded the temperature profiles were indeed two-dimensional for elliptical fins. The fin temperature distribution was higher as the air relative humidity was increased. The elliptic fin efficiency was increased as the major to minor axis ratio was increased, and the fully wet fin efficiency was lower than that for a dry fin by 10–20%. The elliptic fin efficiency is up to 4% higher than the corresponding circular fin efficiencies having the same perimeter for fully dry condition, and the efficiency gain is up to 8% for that of the fully wet condition.

For elliptic fin, literature from [24,25], Brauer was the first author to study the thermal-characteristics of an elliptic finned tube heat exchanger under the dry condition. Jang and Yang presented the thermal–hydraulic characteristics of a four row elliptic finned-tube heat exchanger under the dry and dehumidifying conditions for two elliptic finned-tube heat exchangers with staggered and in-lined arrangements.

Kundu and Das [26] described the two dimensional plane, when a space restriction in one particular side can select eccentric annular fins. The heat exchanger with elliptical fins was studied numerically by authors [27,28] and they reported the heat transfer rate and efficiency increases with a decrease in the axis ratio. It is a well-known fact that the rate of heat transfer decreases with the increase in fin length.

Jang et al. [29] have demonstrated a paper on elliptic fin. Fluid flow and heat transfer over a four-row, elliptic, finned-tube were studied through an experiment and numerically with staggered and ill-line arrangements and one circular finned tube with staggered arrangement. The experimental results indicated that the typical heat transfer constant of all elliptic finned tube was 35–50% of the corresponding circular crammed tube having an identical tube perimeter; whereas the pressure drop for all elliptic finned-tube bank was merely 25–30% of the circulating finned-tube bank configuration.

3.2. Studies on annular elliptical tubes

The authors listed below analyzed the elliptical cylinders and tubes by numerical, analytical and experimental method, Sakr et al. [30], Sheard [31], Ota et al. [32], Bharti et al. [33,34], Badr et al. [35], Alawadhi [36], Alessio [37], Zheng-ming et al. [38], Merker et al. [39], Matos et al. [40] Bagchi et al. [41], Ibrahim et al. [42], Mainardes et al. [43], Li et al. [44], Hamed et al. [45], Badr [46], Matos et al. [47,48], Huang et al. [49].

The following are the advantages of elliptical fins and elliptical tube over another shape:

- Pressure drop due to flow past over the circular tubes can be reduced if the fin is elliptical one.
- Space restriction on one side and enough space in the perpendicular direction will increase the heat transfer rate.
- In general the tubes are formed in elongated shape with their major axes oriented toward the direction of flow; such a design also increases the area of outer surface thus improving overall heat transfer. This has promoted heat transfer and hydrodynamics studies on non-circular tubes and tube bunks.
- There is a reduction of fouling on the external surface of the tubes with non-circular geometry fins due to its lower frontal area and small wake region.
- During film wise condensation, the effective drainage of the condensate film from the external surface of the tube increases the rate of heat transfer.
- There is increasing power density within a given volume and envelope shape.
- The inner flow passage is kept circular to maintain the pressure capability while the outer surface is formed with a given aerodynamic shape to reduce form drag.

4. Studies on pin fins

Heat transfer enhancement is an active and important field of engineering research since increases in the effectiveness of heat exchangers through suitable heat transfer augmentation techniques can result in considerable technical advantages and savings of costs. The following topic discussed about pin fins.

An approximate analytical method has been suggested [50] for solving the governing equation for horizontal pin fins subject to condensation while saturated steam flowing over its under laminar forced convection. A domain decomposition method is used for determination of the temperature distribution, performance and optimum dimensions of pin fins with temperature dependent thermal conductivity under the condensation of steam on the fin surface. From the results, a significant effect on the temperature distribution in the fin and its performances was noticed with the variation in fin-geometric parameters and thermo-physical properties of saturated vapor. Next, a generalized scheme for optimization has been demonstrated in such a way that either heat-transfer duty or fin volume can be taken as a constraint. Finally, the curves for the optimum design have been generated for the variation of different thermo-physical and geometric parameters, which may be helpful to a designer for selecting an appropriate design condition.

The thermal performances of the heat sink with non-uniform fin width designs with an impingement cooling were investigated numerically by [51]. The governing equations were discretized by using a control-volume based finite-difference method with a power-law scheme on an orthogonal non-uniform staggered grid. The coupling of the velocity and the pressure in terms of momentum equations was solved by the SIMPLEC algorithm. The turbulence model was employed to describe the turbulent

structure and behavior. The parameters include the five Reynolds numbers (Re = 5000–25,000), three fin heights (H = 35, 40, and 45 mm), and five fin width designs (Type-1–5). The objective of this study is to examine the effects of the fin shape of the heat sink on the thermal performance. The results showed that the Nusselt number increases with the Reynolds number. The increment of the Nusselt number decreases gradually with the increasing Reynolds number. Furthermore, the effects of fin dimensions on the Nusselt number at high Reynolds numbers were more significant than that at low Reynolds numbers. It is also found that there was potential for optimizing the non-uniform fin width design.

This work experimentally investigated [52] the fluid flow and heat transfer behaviors of jet impingement onto the rotating heat sink. Air was used as an impinging coolant, while the square heat sinks with uniformly in-line arranged 5×5 and 9×9 pin fins were employed. The side length (L) of the heat sink equaled 60 mm and was fixed. Variable parameters were the relative length of the heat sink (L/d = 2.222 and 4.615), the relative distance of nozzle-to-fin-tip (C/d = 0–11), the jet Reynolds number (Re = 5019–25,096) and the rotational Reynolds number (Re = 0–8114). Both flow characteristics of stationary and rotating systems were illustrated by the smoke visualization. Besides, the results of heat transfer indicate that, for a stationary system with a given air flow rate, there was a larger average Nusselt number (Nu0) for the 9×9 pin-fin heat sink with L/d = 4.615 and C/d = 11. For a rotating system, a bigger Rer meant a more obvious heat transfer enhancement (NuX/Nu0) in the case of smaller Re, but NuX/Nu0 decreased with increasing Re. In this work, NuX/Nu0 in L/d = 2.222 is higher than in L/d = 4.615; among the systems in L/d = 2.222, bigger NuX/Nu0 exists in the case of C/d = 9–11, but among the systems in L/d = 4.615, bigger-NuX/Nu0 exists in the case of C/d = 1–3. Finally, according to the base of NuX/Nu0P1.1, the criterion of the substantial rotation was suggested to be Rer/ReP1.154.

The present [53] paper reported on heat transfer enhancement and the corresponding pressure drop over a flat surface equipped with square cross-sectional perforated pin fins in a rectangular channel. The channel had a cross-sectional area of 100–250 mm^2. The experiments covered the following range: Reynolds number 13,500–42,000, the clearance ratio (C/H) 0, 0.33 and 1, the inter-fin spacing ratio (Sy/D) 1.208,1.524, 1.944 and 3.417. Correlation equations were developed for the heat transfer, friction factor and enhance efficiency. The experimental results showed that the use of the square pin fins may lead to heat transfer enhancement. Enhancement efficiencies varied between 1. 1 and 1.9 depending on the clearance ratio and inter-fin spacing ratio. Both lower clearance ratio and lower inter-fin spacing ratio and comparatively lower Reynolds numbers were suggested for higher thermal performance. Using the Taguchi experimental design method, optimum design parameters and their levels was investigated. The Nusselt number and friction factor were considered as performance parameters. An L9 (33) orthogonal array was selected as an experimental plan. First of all, each goal was optimized, separately. Then, all the goals were optimized together, considering the priority of the goals. Finally, the optimum results were found to be Reynolds number of 42,000, fin height of 50 mm and streamwise distance between fins of 51 mm.

Considerable enhancements [54] were demonstrated in the present work by using small cylindrical pins on surfaces of heat exchangers and simple relationships were used for the conductive and convective heat transfer to derive an equation that showed which parameters permit the achievement of heat transfer enhancements. Experiments were reported that demonstrate the effectiveness of the results of the proposed approach.

Detailed experimental investigation [55] of the wall heat transfer enhancement and total pressure loss characteristics for two alternative elliptical pin fin arrays was conducted and the results were compared to the conventional circular pin fin arrays. Two different elliptical pin fin geometries with different major axis lengths were tested, both having a minor axis length equal to the circular fin diameter and positioned at zero degrees angle of attack to the free stream flow. The major axis lengths for the two elliptical fins were 1.67 and 2.5 times the circular fin diameter. Endwall heat transfer and total pressure loss measurements were performed two diameters downstream of the pin fin arrays (X/D = 2) in a rectangular cross-section tunnel with an aspect ratio of 4.8 and for varying Reynolds numbers between 10,000 and 47,000 based on the inlet velocity and the pin diameter. Liquid Crystal Thermography was used for the measurement of convective heat transfer coefficient distributions on the endwall inside the wake. The result showed that the wall heat transfer enhancement capability of the circular pin fin array was about 25–30% higher than the elliptical pin fin arrays on average. However in terms of total pressure loss, the circular pin fin arrays generate 100–200% more pressure loss than the elliptical pin fin arrays. This makes the elliptical fin arrays very promising cooling devices as an alternative to conventional circular pin fin arrays used in gas turbine blade cooling applications.

This paper described a heat transfer by the experimental study of four different internal trailing edge cooling configurations based on pin fin schemes. A circular pin fin configuration with an innovative pentagonal scheme was compared to a standard staggered scheme, while two elliptic pin fin configurations were compared to each other turning the ellipse from the streamwise in the spanwise direction. For each configuration heat transfer and pressure loss measurements were made keeping the Mach number fixed at 0.3 and varying the Reynolds number from 9000 to 27,000. Pin fins were made of high thermal conductivity material and an inverse data reduction method based on a finite element code allows evaluating the mean heat transfer coefficient (HTC) of each pin fin. On the contrary, the HTC map of the two elliptic configurations was similar, but the spanwise arrangement generates higher heat transfer coefficients and pressure losses.

In this work [56] the heat transfer and fluid flow analysis were employed to optimize the geometry of the pin-fin heat sinks. An entropy generation minimization (EGM) method was employed. The performance of the heat sinks was determined by its thermal resistance and pressure drop since they significantly influence the thermal resistance during forced convection cooling. The optimum design of heat sink for in-line and staggered alignments with circular, square, rhombus, rectangular, and elliptical configurations were investigated and the thermal behavior was compared. The result indicated that the geometries of circular and elliptical shapes provide more favorable conditions for heat transfer than that of square, rectangular and rhombus shapes. In all cases, the optimum size of staggered alignment was better than in-line alignment. In a particular pin-fin configuration, the entropy generation rate was comparatively as elliptical > circular > rhombus > rectangular > square pin fins.

The following study [57] will examine the effect on overall thermal/fluid performance associated with different fin geometries, including, rectangular plates as well as square, circular and elliptical pin fins. The use of EGM allows the combined effect of thermal resistance and pressure drop to be assessed. The formulation for the dimensionless entropy generation rate was developed in terms of dimensionless variables, including the aspect ratio, Reynolds number, Nusselt number and the drag coefficient for selected fin geometries. The results clearly indicate that the preferred fin profile was very dependent on the parameter.

The research work [58] summarized in this thesis presents a combined analytical, experimental and numerical investigation of various aspects of single-phase convective heat transfer enhancement by the use of pin fins was presented. The method was

demonstrated on pin fins as elements for the heat transfer enhancement, but it could be applied also to other fin forms. In order to check the applicability of the analytical method, experimental investigations of a double-pipe pin fin heat exchanger were carried out.

The above literature on pin fins concluded that pin fin with elliptical geometry and staggered arrangements has a better heat transfer performance.

5. Studies on longitudinal fins

Very few investigations have been reported on Longitudinal fins. In this section, an overview of the reported investigations is discussed.

Mostafa et al. [59] have presented a paper on the efficiency and optimization of straight fins with combined heat and mass transfer—an analytical solution. During this paper, an analysis was carried out to study the efficiency of straight fins of different configurations when subjected to simultaneous heat and mass transfer mechanisms. In this paper author gave an analytical solution for temperature distribution over the fin surface when the fin is fully wet. A closed-form analytical solution has been obtained for the fin efficiency as well as the total heat transfer rate of straight fins when operating under fully wet conditions. With the aid of this paper we also use to study the effect of atmospheric pressure on the fin efficiency. But the authors of [56] illustrate a novel approach, which integrates the DOE, GA, RSM, MOST, and CFD codes, to provide an efficient system aiming at minimizing the entropy generation for multi-parameter design problems. The entropy generation rate, as a general criterion for designing a heat sink is introduced for their experimental work. The EGM method has been used in thermodynamic system optimization. The authors derived a specific expression of thermal resistance and entropy generation rate of the plate finned heat sinks with both side and also with top bypass flow.

Kundu et al. [60] have presented a paper on performance analysis and optimization of straight taper fins with variable heat transfer constant. In this paper, the thermal analysis and optimization of straight taper fins have been self-addressed. The authors assumed that the fins are of constant thermal conductivity and they exchange heat with the ambient medium solely by convection for their mathematical analysis for three types of fins namely longitudinal, spine and annular with a straight taper. The thermal performance of all the three types of fin has been given with thermo-geometric parameters. The authors observed and gave a conclusion that the variable heat transfer coefficient has a strong influence over the fin efficiency and also, a generalized methodology has been pointed out for the optimum design of straight taper fins.

Kazeminejad [61] has given a paper on analysis of one-dimensional fin assembly heat transfer with dehumidification. The author studied and gave the performance of a cooling and dehumidifying fin assembly. He used the traditional technique which was extended by incorporating the quantitative relation of smart to enthalpy transfer into the analysis of fin assemblies throughout dehumidification.

Thombre et al. [62] have presented a paper on turbulent flow heat transfer and friction factor characteristics of shrouded fin arrays with uninterrupted fins. The authors make experiments to review the absolutely developed flow heat transfer and friction issue characteristics of shrouded, rectangular cross-sectioned longitudinal fin arrays with uninterrupted fins subjected to a homogenous heat flux condition at the fin-base. Based on the heat transfer tests, the authors found that the Petukhov–Popov equation, valid for the smooth rectangular duct with no fins and heating on one face. Also the D–B equation was applicable for all the fin configurations with no clearance or with clearance-to-spacing ratio was too small or with spacing-to-fin height ratio was large.

Kundu [63] has given a paper on performance and optimum design analysis of longitudinal and pin fins with simultaneous heat and mass transfer unified and comparative investigations as shown in Fig. 4. In the present paper, the thermal analysis and optimization of longitudinal and pin fins of uniform thickness subject to fully wet, partially wet and fully dry surface conditions are carried out analytically, and also a comparative study is made between the longitudinal and pin fin for a wide range of design parameters. The optimization analysis has been presented in a generalized form such that either heat transfer duty or fin volume can be treated as a constraint. The author used to derive the optimality criteria by using the Lagrange multiplier technique. In addition, the method for optimization of partially wet surface fins has also been established. The authors conclude that the overall fin efficiency of longitudinal and pin fins for partially wet surface conditions is influenced strongly by the relative humidity. But this effect is less sensitive for the pin fin. However, for the fully wet surface of all types of fins, fin efficiency does not have a noteworthy change with the relative humidity.

6. Studies on fins by recent trends

The main objective in raising the performance of thermal systems is to reinforce the heat transfer between hot and cold surfaces and also the flowing fluid. Numerous ways are projected to attain this task. Some classical techniques on fins are the main interest of this work.

Khaled [64] has given a paper on bi-convection fins. Heat transfers through the fins subjected to two totally different convective media

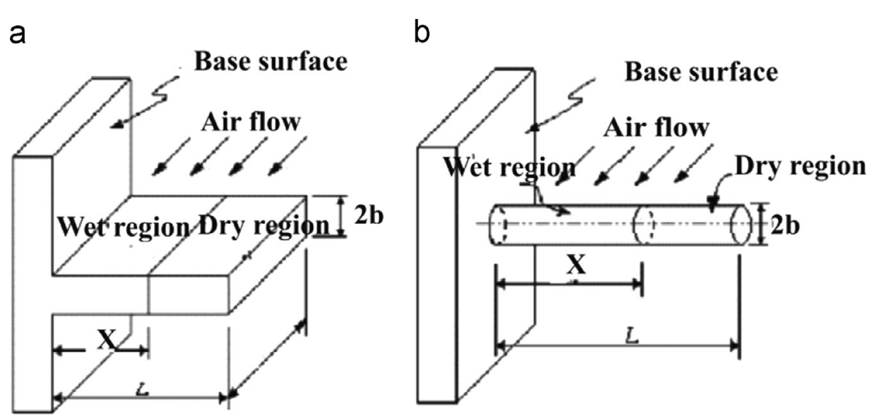

Fig. 4. Schematic diagram of the partially wet surface fin of uniform thickness: (a) longitudinal fin and (b) pin fin.

were analyzed. The "Bi-convection fin" was employed with five totally different cases were Case A: bi-convection thickness-wise bi-metallic fins; Case B: bi-convection span-wise rectangular fins; Case C: bi-convection longitudinal-wise fins; Case D: bi-convection perimeter-wise fins with uniform cross-section; and Case E: bi-convection perimeter-wise pervious fins. Closed type solutions for the fin temperature and warmth transfer rate were obtained. It is found that heat transfer through bi-convection fins were also decreased in Cases A, B, D and E except C.

This study [65] conducted experiments on the optimized fin pitch for crimped spiral fin-and-tube heat exchangers. The experiments covered a size range of 2.4–6.5 mm, which was the manufacturing limitation for this kind of fin. The water-flow arrangement used in this experiment combined the parallel cross-flow and the counter cross-flow in a two-row configuration. Ambient air was used as the working fluid on the air-side, and hot water was used on the tube-side. The effects of fin pitches on the heat transfer coefficient and pressure drop characteristics were studied. The results clearly showed that the convective heat transfer coefficient (ho) for a fin pitch of 2.4 mm was relatively low compared with that of other fin pitches with the same air frontal velocity. Using larger fin pitches (i.e., 4.2, 6.2, and 6.5 mm) resulted in negligible differences in the pressure drop. Moreover, this work introduced the parameter of three performances indexes, which can be expressed as the ratio of the desired output to the required input, for optimization purposes. Due to the difference in optimum fin pitch obtained from these performance indexes, an intersection analysis was conducted. The results indicated that the optimum fin pitch is 4.2 mm for this work, which could be valuable for the effective design for industrial thermal-system applications.

The present study has experimentally [66] performed the investigation of 11 kinds of internally finned tube in Exhaust Gas Recirculation (EGR) cooler. Each internally finned tube has single-tube structure. For internal fin width, fin height, wave number, inscribed circle diameter and fin upwind distance have significant impact on heat transfer and flow resistance loss performances. It has been found that all the internally finned tubes enhance heat transfer significantly. The correlations of the Nusselt number and the friction factor with the Reynolds number were found in the ranges of 1689–Re–5076. The experimental results showed that the friction factor increased with the increase of wave number, while it decreased with the increase of internal fin width and inscribed circle diameter. In addition, when manufacturing the internally finned tube, it is better to select a large upwind distance.

An experimental [67] investigation was carried out to study the single-phase stagnation point jet impingement heat transfer on smooth and micro-pin fin structures using water and R134a. The experiments were carried out for a single jet (dj = 2.0 mm) impinging on a $2 \times 2\ mm^2$ micro-heater over a wide range of Reynolds numbers. Both an unfinned and a micro-structured impingement surface were investigated. The micro-structures consisted of an array of 64 circular micro-pin fins fabricated using MEMS micro-fabrication. The micro-pin fins had diameters of 125 lm, heights of 230 lm, and pitches of 250 limes with an area enhancement of Atotal/Abase = 2.44. The jet stand-off ratio and area ratio (Aj/Abase) were 0.86 and 0.785, respectively. Nusselt numbers were found to increase with increasing Reynolds numbers. Correlations from the literature for impingement zone Nusselt numbers were found to underpredict the experimental results. Significant enhancement of the heat transfer coefficients was observed as a result of the presence of the micro-pin fins on the impingement surface. Enhancement factors as high as 3.03 or about 200% increase in the heat transfer coefficients were demonstrated. Enhancements are attributed to flow mixing, interruption of the boundary layers, and augmentation of turbulent transport.

3-D models were established to study convective heat transfer and fluid flow characteristics of the triangular perforated fin for numerical simulation using the CFD software in [68]. Compared to the related experimental data, the validation of the CFD method was verified. The effects of hole opening ratios and hole stagger arrangements on heat transfer and pressure drop characteristics were investigated. Variation in the Colburn factor j and the friction factor of relative to Re were examined. The performance criteria j/f 1/3 were calculated and superior to the serrated fin under the Reynolds number ranges from 200 to 1960. The inherent mechanism of fluid flow and heat transfer enhancement was explained by the field synergy principle. The average field-synergy angle of B-1/2 was the largest and A-1/4 had the smallest one. The values for A-1/2 were in between. The field synergy principle analysis was consistent with the numerical results. It stated that the secondary flows and vortices can improve the synergy between the velocity and temperature gradient, which is the most fundamental reason why the triangle perforated fin can enhance the heat transfer.

This research [69] discussed about the convective heat transfer characteristics of carbon nanotube coated brass surface under natural convection. Experimentally the temperature distribution of coated and non-coated fins was observed and optimized using the Taguchi method and ANOVA analysis. There was a significant drop in surface temperature for nanocoated brass surface for three different heat inputs. Simultaneously the convective heat transfer increases for coated brass surface due to considerable increase in surface area of carbon nanotube and the huge temperature difference between coated surface and ambient temperature. The individual carbon nanotubes coated on the brass surface almost acts as a pin fin. The average improvement in fin efficiency was 12% for coated brass surface.

An experimental study [70] was conducted to determine the heat removal ability of MWNTs grown in a silicon mini channel with Al_2O_3/H_2O nanofluid as the cooling medium. The use of nanofluid as the working medium in minichannels has also shown a significant increase in thermal performance. To determine the heat removal ability of both multi-walled carbon nanotubes (MWNTs) grown in a silicon minichannel and the use of Al_2O_3/H_2O nanofluid at a volume concentration of 0.01% as the working medium, an experimental investigation was conducted. Minichannel devices containing two different MWNT structures one fully coated surface of MWNTs and the other with a 6–12 (rows, columns) circular staggered fin array of MWNTs—were tested and compared to a minichannel device with no MWNTs. The performance is evaluated based on a constant heat flux applied to the silicon base versus the corresponding silicon base temperature. The experiment was performed at a volumetric flow rate of 80 mL/min for a range of power inputs and was conducted multiple times to understand the extended performance after nanoparticles sediment on the channel surface. It was observed that the sedimentation of Al_2O_3 nanoparticles on a channel surface with no MWNTs increases the surface roughness and the thermal performance. When using both nanofluid and the MWNTs structured surface, the thermal performance had little to no increase for all experimental runs compared to the experiment with using deionized water. With the nanoparticle residue on the initial bare channel surface, the experiment was then run using deionised water and improved thermal performance was achieved.

7. Conclusion

From the cited literature, the following research extensions are identified:

- Optimization and performance of annular fins with elliptical tube heat exchangers would be of direct use by the heat

transfer equipment designers and rating engineers for economic and time saving.

- Thermal designers face a challenge of increasing power density within the volume and envelope shape. Elliptical fins will be a better choice compared to annular and eccentric fins.
- Pin fins with elliptical geometry and staggered arrangements have a better heat transfer performance.
- Efficient design of heat exchanger with fins can improve system performance considerably. Among several available techniques for augmentation of heat transfer in heat exchanger tubes, the use of internal fin appears to be a very promising method as evident from the results of the past investigations. This is especially important in modern electronic systems, in which the packaging density of circuits is high. In order to overcome this problem, thermal systems with effective emitters as fins are desirable.
- Coating on fins increase the heat transfer rate. Only very few researchers focussed on nanocoating on extended surfaces. Future work may concentrate on this. From the review it is clear that multi-wall carbon nanotubes act as a pin fin to enhance the surface area for effective convective heat transfer rate.

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